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Julie Meimoun, Vincent Wiatz, René Saint-Loup, Julien Parcq, Adéline David, et al.. A one pot one step combined radical and ring-opening route for the dual functionalization of starch in aqueous medium. Carbohydrate Polymers, 2021, Carbohydrate Polymers, pp.117399. 10.1016/j.carbpol.2020.117399 . hal-03017282

HAL Id: hal-03017282

<https://hal.science/hal-03017282>

Submitted on 20 Nov 2020

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A one pot one step combined radical and ring-opening route for the dual functionalization of starch in aqueous medium

Julie Meimoun,^a Vincent Wiatz,^b René Saint-Loup,^b Julien Parcq,^b Adéline David,^c Grégory Stoclet,^c Valérie Gaucher,^c Audrey Favrelle-Huret,^a Fanny Bonnet,^c Philippe Zinck^{a*}

^a Univ. Lille, CNRS, Centrale Lille, ENSCL, Univ. Artois, UMR 8181 - UCCS - Unité de Catalyse et Chimie du Solide, F-59000 Lille, France.

^b Roquette Frères, F-62080 Lestrem Cedex, France.

^c Univ. Lille, CNRS UMR 8207 – UMET - Unité Matériaux et Transformations (UMET), F-59000 Lille, France.

Starch based materials are attractive bio-based alternative to fully synthetic polymers. Native starch has however limited thermoprocessability and properties and must be modified. In order to improve the properties of starch-graft-poly(butyl-acrylate-*co*-styrene) copolymers via a process as green as possible, we report herein a new method for the dual functionalization of the polysaccharide via a one pot one step reaction in aqueous medium combining free radical polymerizations and ring-opening chemistry. Poly(butyl acrylate) / poly(butyl acrylate-*co*-styrene) (ca. 60 000 g/mol) and oligo(ϵ -caprolactone) were grafted on starch with a grafting percentage up to 75 %. The copolymers show two glass transition temperatures: one around 55-60°C related to starch and a second attributed to the grafted vinyl polymers, from -46°C to 20°C depending on butyl acrylate/styrene ratio). The resulting dual functionalized materials exhibit excellent mechanical properties, with elongation at break in the range 20-210 %, while single functionalized starch shows less than 5 %.

Keywords: starch, graft copolymerization, structural / thermomechanical properties.

1. Introduction

Research towards biobased and biodegradable polymers has received much attention this last decade, due notably to environmental concerns and the depletion of oil resources (Chen, Kamitakahara & Edgar, 2020; Imre, García, Puglia & Vilaplana, 2019). In this context, starch is a promising starting material due to its availability and low cost that has been the subject of numerous studies (Chen et al., 2015; Fan & Picchioni, 2020). However, starch has limited thermoprocessability along with a strong hydrophilic character and poor mechanical properties as compared to conventional synthetic polymers (Avérous & Halley, 2009). Starch can be plasticized with external plasticizers such as polyols (Lourdin, Coignard, Bizot & Colonna, 1997), urea/formamide combinations (Xiaofei, Jiugao & Jin, 2004) notably. However, some shortcomings, as plasticizer migration, induce an evolution of its properties over time and thus limit its applications.

To overcome some of these drawbacks, the polysaccharide can be blended with synthetic polymers (Wang, Yang & Wang, 2003), functionalized to yield starch esters and ethers (Aburto, Alric & Borredon, 1999; Shogren, 2003) or grafted with a polymer (Meimoun et al., 2018; Cazotti et al., 2020; Haq et al., 2020). Graft copolymerization is a very versatile way of functionalization allowing access to materials displaying a combination of the properties of the synthetic polymer and of the starch (Jyothi,

2010). In particular, the radical graft copolymerization can lead to starch-based materials with interesting properties. In this frame, the synthesis of starch/starch-*graft*-poly(butyl acrylate-*co*-styrene) copolymers by free-radical graft polymerization was conducted on native (Meshram, Patil, Mhaske & Thorat, 2009), acetylated (Mou, Li, Wang, Fei & Liu, 2012) starch and dextrin (David et al., 2019). Starch can also be modified by grafting polyesters on its backbone by ring-opening polymerization (ROP) in organic solvents (Chen et al., 2005; Rutot-Houzé et al., 2004) and in water (Choi, Kim & Park, 1999), a tin based catalyst being used for this purpose.

The combination of the two processes, *i.e* radical and ring-opening grafting onto polysaccharides can give access to advanced materials with applications such as drug, fragrance containers or stimuli responsive materials (Chang, Yamabuki, Onimura & Oishi, 2008; Liu, Huang, Pang, Han & Ji, 2015; Yan et al., 2009). Diblock copolymers were grafted onto cellulose by combining in a sequential way ROP and Atom Transfer Radical Polymerization (ATRP), involving the use of copper halide, amine ligands and, in the examples reported herein, 2-bromopropionyl bromide (Berthier, Herrmann & Ouali, 2011; Östmark, Nyström & Malmström, 2008). In these studies, polyester is grafted as the first block by ROP of a cyclic ester, eventually after a first protection step of a part of the hydroxyl groups. The polymer chain end is further derivatized to yield an initiator for the controlled radical polymerization of a second monomer, leading to the second block.

The dual functionalization, *i.e* the grafting of two different oligo/polymers was reported onto cellulose powder and cellulose derivatives such as hydroxyethylcellulose or diacetate cellulose by a multistep procedure involving the grafting of the controlled radical polymerization initiator (Chang, et al., 2008; Liu et al., 2015; Vlček et al., 2008). As a representative example, the radical macroinitiator is formed at the first step by the reaction of hydroxyl groups with 2-bromopropionyl bromide in a mixture of tetrahydrofuran (THF) and trimethylamine. The tin catalyzed ring-opening polymerization of ϵ -caprolactone initiated by the remaining hydroxyl groups is then realized in xylene, followed by the ATRP of *N,N*-dimethylaminoethyl methacrylate in THF in the presence of *N,N,N',N'',N'''*-pentamethyldiethylenetriamine (PMDETA) and CuBr (Yan et al., 2009).

The combination of radical and ROP processes was, as far we know, reported onto cellulose and never onto starch. The synthetic strategies reported in the literature involved multistep procedures, the use of organic solvents (*e.g* THF, xylene), harmful compounds for the initiation of the controlled radical polymerization (*e.g* copper halide, brominated derivatives) and tin catalyzed ring-opening polymerizations. In order to improve the properties of starch-*graft*-poly(butyl acrylate-*co*-styrene) copolymers, we developed in this contribution a greener process for the dual functionalization of polysaccharide via free-radical graft polymerization and ring-opening functionalization, using phosphoric acid as organocatalyst for the latter, and a one pot one step process in aqueous medium. The new bi-functionalized materials developed herein exhibit remarkable elongations at break, highlighting promising potentialities for stretchable films. The microstructure of copolymers is studied by Nuclear Magnetic Resonance (NMR), Fourier Transform Infrared Spectroscopy (FT-IR), Size Exclusion Chromatography (SEC), Differential Scanning Calorimetry (DSC) and Thermal Gravimetric Analysis (TGA).

2. Experimental

The Materials and Characterization procedures are presented in the Appendix A.

Grafting reactions

For all reactions, dry starch (30 g) was gelatinized in 120 mL water by heating at 95 °C for 30 minutes. The temperature was then decreased to 85 °C. This leads to the disappearance of the granular structure of starch. The chains are then more accessible for the grafting.

- Free radical grafting

Sodium peroxydisulfate (1 mol % *vs.* starch) previously dissolved in 10 mL of water, butyl acrylate (BA) and/or styrene (St) (70-75 wt % *vs.* starch) were added dropwise for 1 h. The grafting

polymerization was carried out for 30 additional minutes. A few experiments carried out under inert atmosphere to avoid oxygen led to similar grafting ratio and microstructures than those conducted under air. The latter experimental conditions were thus chosen for the work.

- *Ring-opening grafting*

Phosphoric acid (1 mol % vs. ϵ -caprolactone), ϵ -caprolactone (CL) (25 wt % vs. starch) were added dropwise for 1h. The grafting polymerization was carried out for an additional 4 h.

- *One pot one step free radical and ring-opening grafting*

Sodium peroxydisulfate (1 mol % vs. starch) and phosphoric acid (1 mol % vs. ϵ -caprolactone) previously dissolved in 10 mL of water were added dropwise for 1h via dropping funnel. At the same time, monomers: butyl acrylate and/or styrene (70-75 wt % vs. starch) and ϵ -caprolactone (25-30 wt % vs. starch) were added dropwise for 1 h via second dropping funnel. The grafting polymerization was carried out for an additional 4 h.

- *Sequential free radical and ring-opening grafting*

Sodium peroxydisulfate (1 mol % vs. starch) previously dissolved in 10 mL of water, butyl acrylate and/or styrene (70-75 wt % vs. starch) were added dropwise for 1 h. The grafting polymerization was carried out for an additional 30 minutes. Then, phosphoric acid (1 mol % vs. ϵ -caprolactone), ϵ -caprolactone (25-30 wt % vs. starch) were then added dropwise for 1h. The grafting polymerization was carried out for an additional 4 h.

At the end of the reaction, for each process, the solution was poured in acetone and left during 24 h under magnetic stirring to remove the ungrafted polymer. The product was filtered and dried overnight. The procedure of purification was validated on a few samples by Soxhlet extraction in chloroform during 24 h that led to the same ratio.

The weight grafting percentage (GP) was determined by gravimetry as following:

$$\text{GP} = \frac{[(\text{weight copolymer} - \text{weight of starch}) / \text{weight of starch}] \times 100}{= [\text{weight of grafted polymer} / \text{weight of starch}] \times 100}$$

3. Results and discussion

3.1. Grafting reaction

3.1.1 Syntheses of starch-graft-poly(butyl acrylate) and starch-graft-oligo(ϵ -caprolactone): single starch functionalization

Entries representative of the grafting reactions starting from butyl acrylate and ϵ -caprolactone on the starch via the different routes are presented in Table 1. Brönsted acid catalysis using phosphoric acid was chosen for the ring-opening since the molecule is harmless at low concentration (it is found in sodas) and it was already used successfully by some of us to graft oligo(ϵ -caprolactone) on dextran and methylated cellulose in aqueous medium (Stanley et al., 2014). Radical and ring-opening functionalizations were first assessed separately. The free radical graft copolymerization of butyl acrylate in water (entry 1) leads to an almost quantitative efficiency, as reported previously (David, 2019). Rather long chains are grafted, with a number-average molecular weight of 80 300 g/mol, and a significant dispersity. The resulting degree of substitution (DS) is consequently low, around 0.0014.

Regarding the mechanism, the decomposition of potassium persulfate in aqueous medium containing an alcohol is described in the literature (Bartlett & Cotman, 1949). The formation of only $^{\circ}\text{CH}_2\text{OH}$ radicals in methanol has been confirmed by Electron Spin Resonance (Norman, Storey & West, 1970). Indeed, radicals are more likely located on the carbon in α position of the oxygen rather

Table 1 Dual functionalization of starch in aqueous medium: initial assessment ^a

Entry	Route ^b (time)	BA/CL ^c (% wt)	GP ^d (%)	GP _{BA} ^e (%)	GP _{CL} ^e (%)	DS ₁ ^f	DS ₂ ^f	M _n ^g (g/mol)	M _{n corr} ^g (g/mol)	\bar{D}_M ^g	T _{g1} ^h (°C)	T _{g2} ^h (°C)	T _{deg 1} ⁱ	T _{deg 2} ⁱ	σ^j (MPa)	ϵ^j (%)
1	Radical (1.5 h)	75/0	69	69	-	0.0014	-	154 000	80 300	6.3	-46	56	254	343	0.3 ± 0.1	1.6±0.4
2	ROP (5 h)	0/25	1.6	-	1.6	0.0223	-	116 ^k	-	-	-	61	-	-	-	-
3	Dual (5 h) <i>Simultaneous</i>	75/25	69	62.5	6.5	0.0953	0.0337	60 800	34 200	3.8	-46	55	250	345	0.9 ± 0.5	2 ± 0.3
4	Dual (1.5 + 5 h) <i>Sequential</i>	75/25	72	68.9	3.1	0.0484	0.0191	44 000	25 500	7.7	-45	59	249	345	0.5 ± 0.1	2 ± 0.5

^a The starch was heated at 95 °C for 30 min in water before the grafting reaction at 85 °C.

^b Sodium peroxydisulfate (1 mol % *vs.* starch) and phosphoric acid (1 mol % *vs.* CL) as initiator and catalyst

^c wt % monomer in the feed *vs.* starch

^d Overall grafting percentage determined by gravimetry

^e GP_{PBA} (%) GP_{oligo(CL)} (%) are the grafting percentage of poly(butyl acrylate) and poly(ϵ -caprolactone), respectively, determined by ¹H NMR analysis in DMSO-d₆/CDCl₃ (50/50) (see Appendix B)

^f Degree of substitution, see Appendix A.2. For entries 3 and 4, DS₁ and DS₂ (DS_{PBA} + DS_{PCL}) are determined with the hypothesis of DP_n of 1 and 3, respectively, for oligo(ϵ -caprolactone) because when the grafting was conducted by ROP only, the grafted chains were composed on average of a single caproyl unit.

^g Number-average molecular weight as measured M_n and corrected using Mark-Houwink-Sakurada factors M_{n corr} and dispersity \bar{D}_M of the grafted poly(butyl acrylate) chains determined by SEC (40 °C, THF, polystyrene standards) after acid hydrolysis (Appendix A.2)

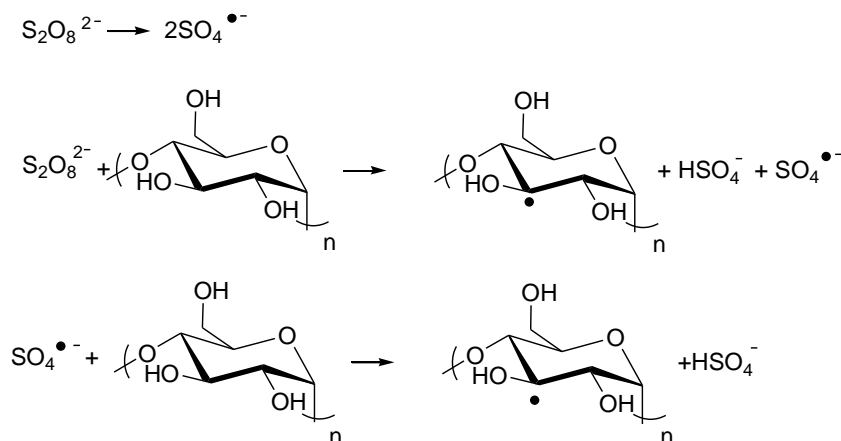
^h Glass transition temperature (T_g) determined by DSC

ⁱ Temperature of degradation determined by TGA (degradation 1: starch, 2: grafted chains)

^j Maximum stress and elongation at break from tensile strength measurement

^k M_n determined by ¹H NMR analysis in DMSO-d₆ (DP_n = 1.02, see Appendix D)

than on the oxygen, and are more stable on more substituted carbons (Giese, 1986). Thus, it is likely that the functionalization occurs preferentially on the carbons located on the sugar ring. Considering this, we propose the initiation mechanism presented in Scheme 1 (the position 3 has been chosen arbitrarily).



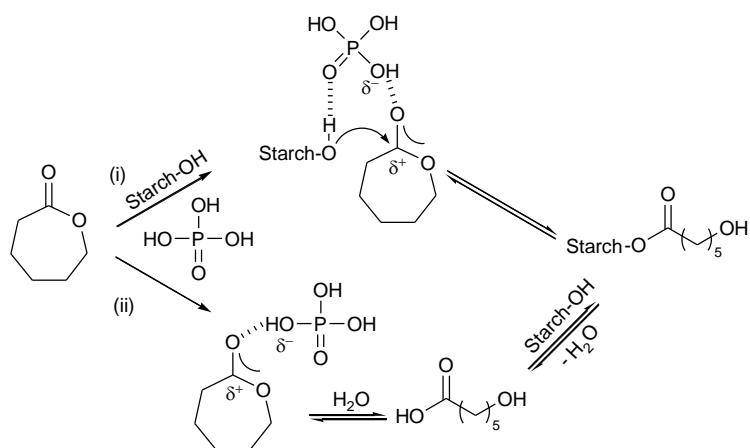
Scheme 1. Proposed radical initiation mechanism in the presence of potassium persulfate in aqueous medium

The grafting conducted by ring-opening of the cyclic ester leads to a more modest grafting ratio (entry 2). ^1H NMR analysis shows that the grafted chains are composed on average of a single caproyl unit (number-average degree of polymerization estimated at 1.02, Appendix D), providing a starch hydroxyester compound. This result can be explained by the use of water as the solvent of the reaction, which can either initiate the ROP of ϵ -caprolactone or enable polycondensation via hydroxyacids resulting from the hydrolysis of the lactone (Scullion & Zinck, 2012), both routes leading to the formation of oligomers or polymers that are not grafted to the polysaccharide. To improve the yield and DP, it would have been interesting to use less water or remove it during the reaction but in this case the viscosity of the medium would be too important. It should be noted that the lactone conversion is quantitative (^1H NMR analysis given in the Appendix E). The resulting DS is *ca.* 20 times higher than the one obtained by the radical route, around 0.022 in these experimental conditions.

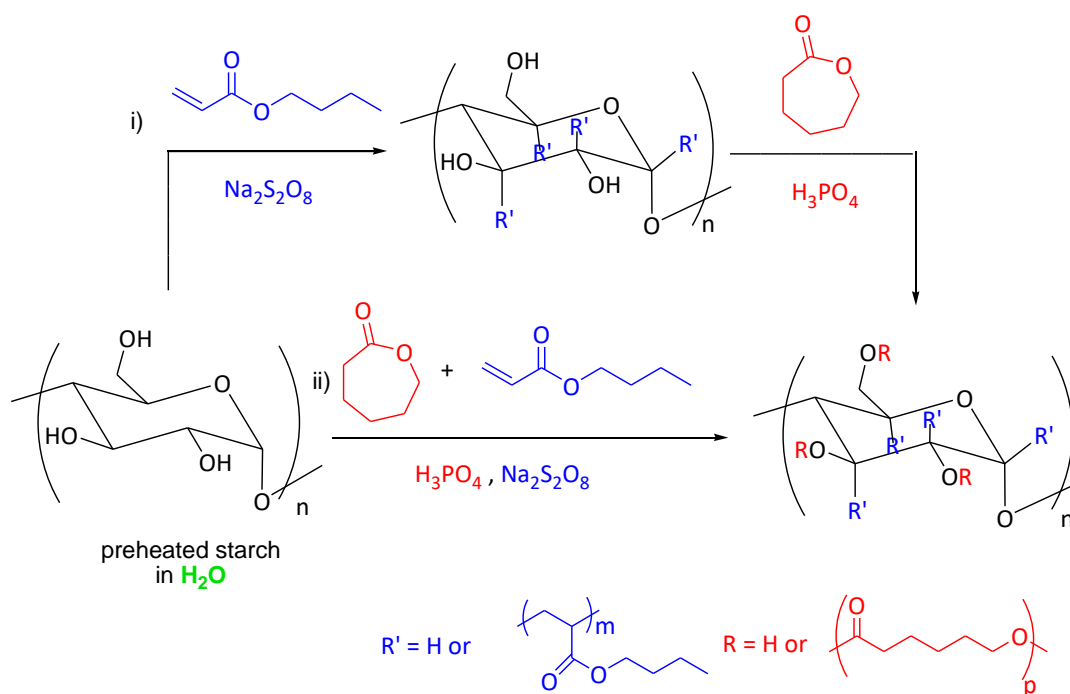
Regarding the grafting mechanism, one can either expect (i) a nucleophilic attack of the carbohydrate hydroxyl on the lactone catalyzed by phosphoric acid, or (ii) the aforementioned hydrolysis of the lactone followed by a condensation reaction between the so formed hydroxyacid and the carbohydrate hydroxyl. This is represented in Scheme 2. Regarding the regioselectivity, we know from our previous work (Miao et al., 2013) that both primary and secondary carbohydrate hydroxyls can be engaged in a transesterification reaction with ϵ -caprolactone in the presence of phosphoric acid moieties. If the pathway (i) is the main mechanism, then we do not expect the reaction to be regiospecific. For the condensation pathway (ii), primary alcohols are known to be more reactive in esterification reactions than secondary alcohols. Thus, if this pathway (ii) is the main mechanism, it is likely that primary alcohols are more involved than secondary alcohols.

3.1.2 Syntheses of starch-*graft*-[poly(butyl acrylate)/oligo(ϵ -caprolactone)]: dual fonctionnalization

The one pot one step combination of the radical and the ring-opening routes in water (represented in Scheme 3) is presented entry 3 and the resulting ^1H NMR spectrum is shown Fig.1. The assignments were made from the ^1H NMR spectra of the starch and of poly(butyl acrylate) that are given in the Appendix B.



Scheme 2. Proposed ring-opening mechanism in the presence of ϵ -caprolactone and phosphoric acid in aqueous medium.



Scheme 3. One pot one step combined radical and ring-opening route for dual (i: sequential, ii: simultaneous) functionalization of starch in aqueous medium

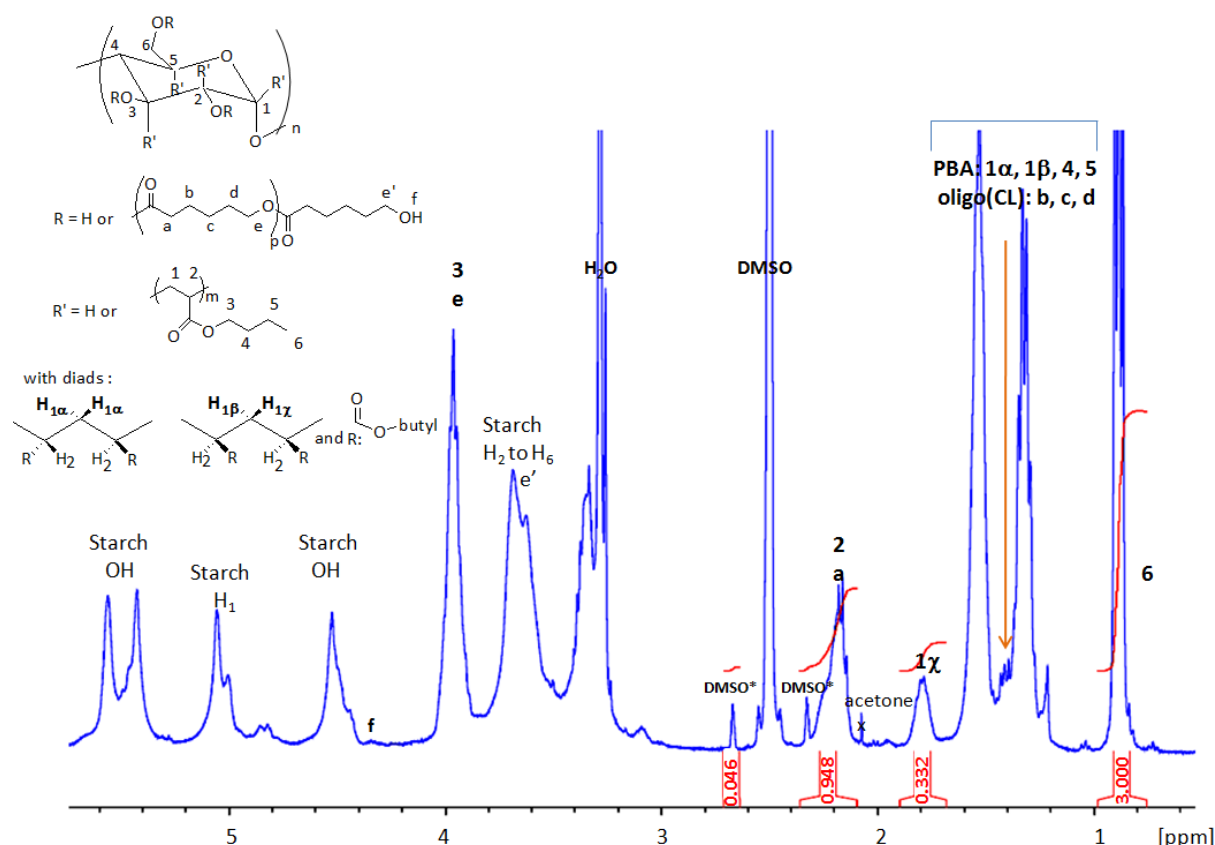


Fig. 1. ^1H NMR spectrum of the starch-graft-[poly(butyl acrylate)/oligo(ϵ -caprolactone)] obtained entry 3 in a mixture of $\text{DMSO-}d_6/\text{CDCl}_3$ (50/50, 400 MHz)

In particular, the $-\text{CH}_2$ signal of the poly(butyl acrylate) backbone is split into three due to the presence of both *meso* and *racemic* diads (Brar, Kumar & Kaur, 2002). The caproyl and butyl acrylate signals are overlapping due to the similarity of the molecules, even if a $\text{CH}_2\text{-CH}_2\text{-CH}_2$ caproyl signal can be evidenced around 1.4 ppm (shown by the arrow in Fig. 1). Signals representative of caproyl units can also be seen on the ^{13}C NMR spectra of the compounds given in Appendix C. Both butyl acrylate and ϵ -caprolactone are thus grafted, showing that the two reactions can occur simultaneously in water, and validating the proof of our concept. If the overall grafting percentage is similar to entry 1, the grafting ratio of the lactone is significantly improved, by a factor 4. Experiments conducted without the starch (reported Appendix F) show that this increase of the grafting efficiency may neither be due to a radical grafting of poly(butyl acrylate) on oligo(ϵ -caprolactone) nor to a transesterification between acrylate and caproyl units. It may thus be attributed to the hydrophobic character of the PBA grafts which could lead to an increase in the lactone and/or oligo(ϵ -caprolactone) concentration in the vicinity of the polysaccharide. The combination of the two chemistries leads to PBA grafts that are significantly shorter than those obtained by the single radical process. Regarding ϵ -caprolactone, the hydrolyzed grafts were found to be soluble in the aqueous phase containing the hydrolyzed starch chains and thus could not be isolated. This is likely due to a very low number-average degree of polymerization, related to the order of magnitude of 1 found by ^1H NMR for a single ring-opening grafting (entry 2).

Experiments combining radical and ring-opening routes were also conducted consecutively, in a two steps reaction, for the sake of comparison. One can start either by the radical route or by the ring-opening one. We obtained significant grafting ratios for the consecutive process starting from the free radical grafting reported entry 4. A slightly higher grafting ratio is obtained, with a lower amount of cyclic ester, leading to a lower DS. The molecular weight of the graft is in the same order of magnitude, yet slightly lower. The two steps consecutive reactions starting from ring-opening followed by radical grafting led to poor results and will not be discussed here.

Even if the DS is low, the process can be considered viable as high GP and M_n grafted are obtained for vinyl grafted. The grafting ratio of oligo(ϵ -caprolactone) is improved by 4 via the combination of two routes of polymerization in aqueous medium compared to ROP alone.

3.1.3 Syntheses of starch-graft-[poly(butyl acrylate-*co*-styrene)/oligo(ϵ -caprolactone)]

The combination of radical and ring-opening grafting was then realized using styrene as a comonomer with butyl acrylate for the radical polymerization. The insertion of styrene into poly(butyl acrylate) is expected to have an impact on the properties of the resulting materials, by *e.g.* modulating the thermal and mechanical properties. Representative results are given entries 6 and 9 in Table 2 together with the reactions conducted in the sequential way (7 and 10) and via the single radical route (5 and 8) for comparison.

Table 2. Dual functionalization of starch in aqueous medium with styrene and butyl acrylate as vinyl comonomers^a

Entry	Route (time) ^b	BA/St/CL ^c (% wt)	GP ^d (%)	BA/St ^d (%)	M_n^e (g/mol)	\bar{D}_M^e	T_{gl}^f (°C)	T_{g2}^f (°C)	$T_{deg\ 1}^g$	$T_{deg\ 2}^g$
5	Radical (1.5 h)	50/25/0	64	62/38	91 300	4.4	4	59	250	356
6	Dual (5 h) <i>Simultaneous</i>	50/25/25	71	67/33	63 200	2.5	-1	56	252	351
7	Dual (1.5 + 5 h) <i>Sequential</i>	50/25/25	72	68/32	71 000	2.9	0	56	245	352
8	Radical (1.5 h)	35/35/0	65	47/53	85 900	2.8	20	57	253	357
9	Dual (5 h) <i>Simultaneous</i>	35/35/30	65	49/51	63 500	2.3	18	58	248	359
10	Dual (1.5 + 5 h) <i>Sequential</i>	35/35/30	75	48/52	59 000	2.8	18	58	249	359

^a The starch is heated at 95 °C for 30 min in water before the grafting reaction at 85 °C.

^b Sodium peroxydisulfate (1 mol % *vs.* starch) and phosphoric acid (1 mol % *vs.* CL) as initiator and catalyst

^c wt % monomer in the feed *vs.* starch

^d Overall grafting percentage determined by gravimetry, ratio of BA/St units in grafted chains was determined by ¹H NMR analysis in DMSO-*d*₆/CDCl₃ (50/50) (Appendix G)

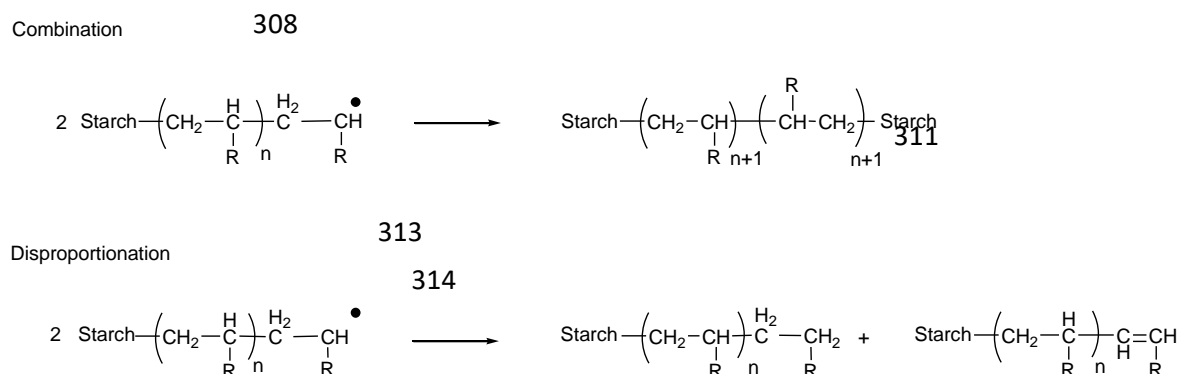
^e Number-average molecular weight M_n and dispersity \bar{D}_M of the grafted poly(butyl acrylate-*co*-styrene) chains determined by SEC (40 °C, THF, polystyrene standards) after acid hydrolysis (Appendix A.2)

^f Glass transition temperature determined by DSC

^g Temperature of degradation determined by TGA (degradation 1: starch, 2: grafted chains)

The resulting grafting percentage is in the same order of magnitude than the one obtained using only butyl acrylate in similar conditions (*e.g.* entries 5-6-7 *vs.* 1-3-4). The determination of the individual grafting ratio, *i.e.* poly(butyl acrylate-*co*-styrene) *vs.* oligo(ϵ -caprolactone) is not possible by the ¹H NMR method used previously due to signal overlapping, and we did not find any other suitable method despite several trials. However, the ratio of butyl acrylate *vs.* styrene units in the grafted chains could be determined by ¹H NMR analysis as reported in the Appendix G. It can be seen that the composition of the poly(butyl acrylate-*co*-styrene) grafts follows the monomer feed. The molecular weights follow the same trends as those observed while grafting PBA, *i.e.* M_n values lower than those obtained from the radical process alone, the difference between the two processes being less important in the presence of styrene. This could be explained by radical chains scissions. It is indeed known that acrylates favor the

occurrence of termination reaction by disproportionation while termination by combination is the main process with styrene as the monomer (see Scheme 4) (Nakamura & Yamago, 2015). This may also explain that the dispersities observed in the presence of the three monomers are lower than those observed in the absence of styrene (2.5-4.4 vs. 3.8-7.7).



Scheme 4. Termination reactions by combination and disproportionation

The copolymers were analyzed by FT-IR (spectra in the Appendix H). The presence of the bands at 1730 cm⁻¹ (ν(C=O)), at 1250 cm⁻¹ (ν(C-O)), and at 700 cm⁻¹ (deformation of aromatic function) are characteristic of the butyl acrylate, caproyl and styrene groups respectively. The stretching frequencies for ν_{as}(CH₃) and ν_s(CH₃) (corresponding to methyl of butyl chain) are observed at 2960 and 2872 cm⁻¹, respectively.

3.2 Thermal analyses

DSC analyses carried out on the grafted copolymers at 50 % relative humidity (thermograms in the Appendix I) reveal two glass transition temperatures (T_g) for all samples involving the radical process, that are given in Table 1 and Table 2. The T_g at -46 °C observed for entries 1; 3-4 corresponds to the T_g of poly(butyl acrylate). The second T_g is found around 55 to 59 °C for all samples, whatever the composition of the grafts, and is attributed to the glass transition of the starch backbone. The starch alone has indeed a T_g around 60 °C in similar conditions. When styrene is used as a comonomer for the radical process, the low T_g found around 2 °C (entries 5-7) and 19 °C (entries 8-10) increases with increasing amount of styrene, the T_g of polystyrene being around 100 °C. The presence of a single T_g for poly(butyl acrylate-*co*-styrene) grafted chains confirms a statistical microstructure which can be expected from the reactivity ratios of the two monomers, r_{St} 0.73-0.87 and r_{BA} 0.17-0.30 (Fernández-García et al., 2000). The thermograms did not show oligo(ε-caprolactone) glass transition or melting temperatures, which can be ascribed to the low grafting ratio and the short size of the grafts. The observation of two T_g by DSC is an indication of a phase separation between starch and the grafted polymer, which was already observed by us on starch-*graft*-poly(butyl acrylate) and starch-*graft*-polystyrene copolymers in the form of two co-continuous phases (transmission electron microscopy analyses, David et al., 2019).

TGA analyses were performed on the graft copolymers (Tables 1 and 2, curves in the Appendix J). On all products, evaporation of water (contained in starch) below 100°C is observed. The unmodified starch substrate degrades from 250 °C. Two main degradation stages are observed on the copolymers: degradation of the starch part from 250 °C and degradation of grafted chains from 340 °C (entries 1-4) or 350°C (entries 5-10). Adding styrene units on the copolymer increases the stability of the grafting chains. The short grafts of oligo(ε-caprolactone) may degrade on the same stage as that of starch. Indeed,

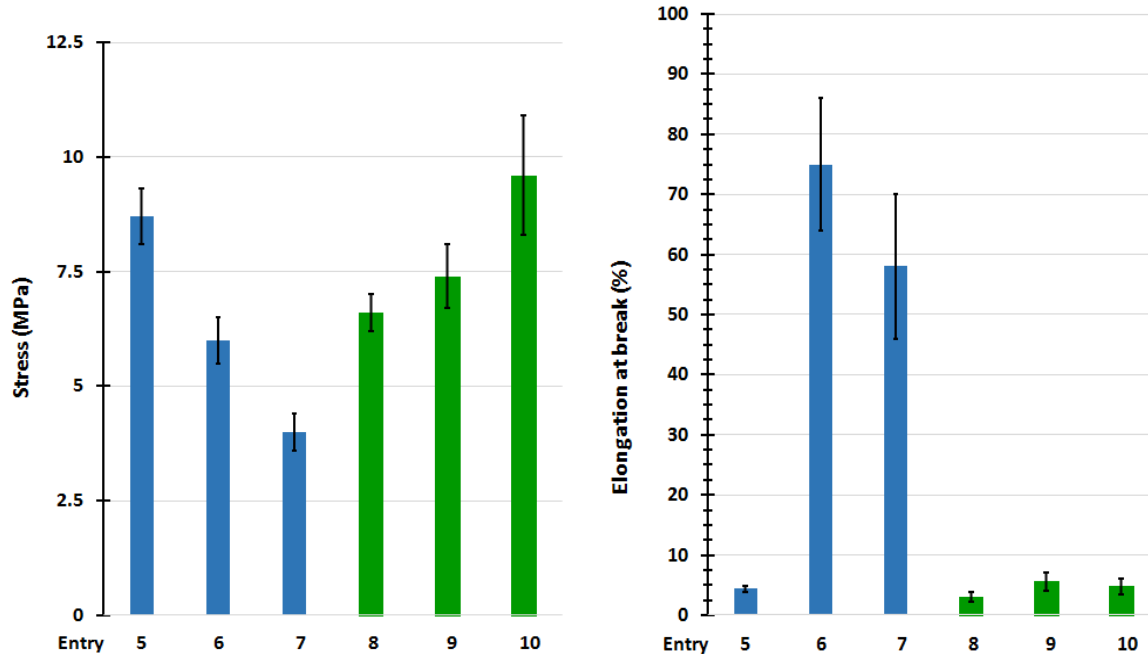
for example starch acetates degrade in one stage of decomposition, the degradation being shifted towards higher temperatures with increasing DS (Wang et al., 2008).

3.3 Mechanical behaviour

Mechanical tests were then performed at 50 % relative humidity and room temperature. The results are presented in Table 1 (entries 1-4) and Figure 2A (entries 5-10). The temperature at which the mechanical tests were conducted is thus above the T_g of the grafted chains, which are as a consequence at the rubbery state, except for entries 8-10 where the T_g of the grafted chains is around 20 °C, and below the T_g of the starch. The copolymers obtained via single free-radical grafting copolymerization exhibit modest mechanical properties, with a stress at break around 0.3 MPa and an elongation at break close to 1.6 % (entry 1). The replacement of one third butyl acrylate by styrene in the feed allows to increase these properties to 8.7 MPa and 4.4 %, respectively, for the starch-*graft*-poly(acrylate-*co*-styrene) copolymer of entry 5. If the combination of the radical and ring-opening routes has a modest effect when butyl acrylate is used as a single radical monomer (entries 3 *vs.* 1), it leads to an impressive increase of the elongation at break when performed in the presence of 25% styrene (entries 6 *vs.* 5), by a factor as high as 17. When the radical grafting is performed with an equimolar amount of styrene and acrylate, the combination of the processes leads in turn to an increase of the stress at break from 6.6 to 7.4 MPa (entries 9 *vs.* 8), with a smooth increase of the elongation at break. The sequential route leads to similar results, with however a lower elongation at break (entry 7 *vs.* 6).

Both routes lead to similar performances in terms of GP, Mn, and thermal properties. The simultaneous route leads in turn to higher elongation at break. The promising results obtained in entry 6 (BA/St/CL 50/25/25, $\varepsilon = 75$ %) prompted us to go further in this direction.

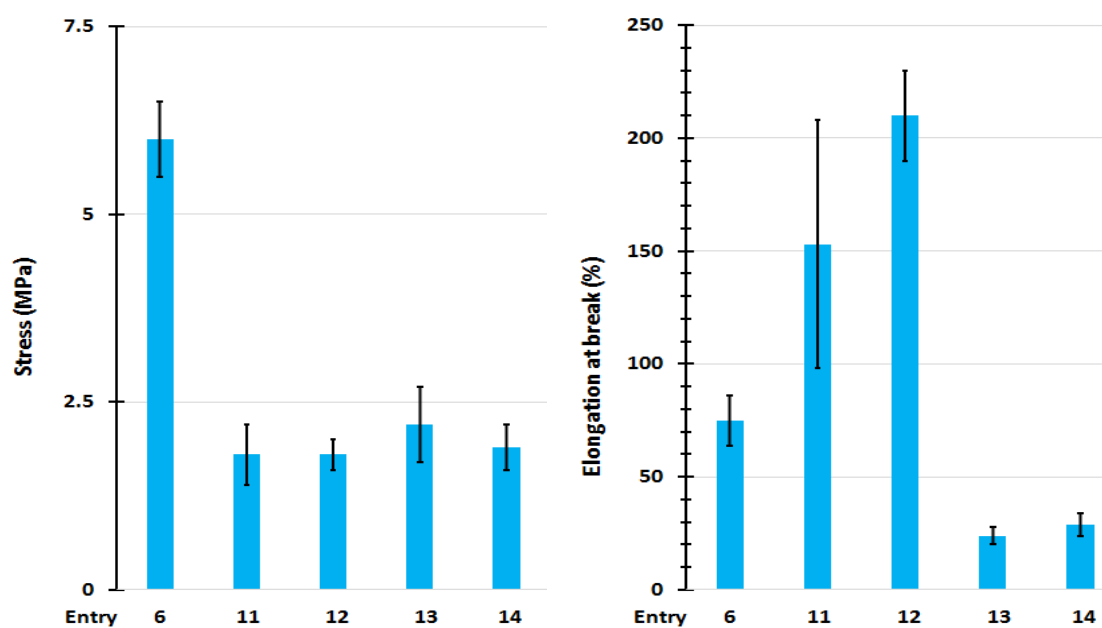
A : Copolymers Entries 5-10 (Table 2)



**5 : Radical (50%BA / 25%St)
(35%BA / 35%St)**

8 : Radical

B : Copolymers Entries 6, 11-14 (Table 3)



6 : 50%BA / 25%St / 25% CL

Dual Simultaneous

13 :

Fig 2 Stress and elongation at break of starch-graft-[poly(butyl acrylate-co-styrene) / oligo(ϵ -caprolactone)] at 20 °C, 50 % RH (numerical values Appendix K) in function of the monomers ratio (wt% vs. starch).

3.5 Final adjustment of feed ratio: optimization of mechanical behaviour

A fine modification of the feed was realized in order to assess the effect of the composition on the mechanical properties in this range. The results are reported in Table 3 and Fig. 2B (the mechanical curves are presented in the Appendix K).

Table 3 Simultaneous dual functionalization of starch in aqueous medium: optimization of the elongation at break^a

Entry	BA/St/CL ^b (% wt)	GP ^c (%)	M _n ^d (g/mol)	\bar{D}_M ^d	T _{g1} ^e (°C)	T _{g2} ^e (°C)
6	50/25/25	71	63 200	2.5	-1	56
11	50/20/30	69	62 000	2.8	-5	60
12	55/20/25	72	64 000	3.0	-10	59
13	55/15/30	68	66 000	2.6	-17	53
14	60/15/25	73	63 000	3.0	-21	57

^a The starch is heated at 95 °C for 30 min in water before the grafting reaction at 85 °C for 5 h. Sodium peroxydisulfate (1 mol % vs. starch) and phosphoric acid (1 mol % vs. CL) as initiator and catalyst.

^b wt % monomer in the feed vs. starch

^c Overall grafting percentage determined by gravimetry

^d Number-average molecular weight M_n and dispersity \bar{D}_M of the grafted poly(butyl acrylate-*co*-styrene) chains determined by SEC (40°C, THF, polystyrene standards) after acid hydrolysis (Appendix A.2)

^e Glass transition temperature determined by DSC

The fine variation of the monomer ratios has neither a substantial influence on the grafting percentages (68-73 %), nor on the molecular weight distributions of the polyvinyl grafts (M_n values 62 000 to 66 000 g/mol and dispersities 2.6 to 3). The T_g of the grafted chains was found to be below 0 °C whatever the ratios. Mechanical tests performed on these materials reveals elongations at break from *ca.* 20 % up to 207 % in this composition range (Fig. 2B.) The composition yielding to the higher elongation (BA/St 55/20) was assessed without the lactone, leading to a value of 14%. An increase factor of *ca.* 15 is thus confirmed while combining the two grafting processes for making the dual functionalized material. It is worth noting that the grafting of a small quantity of oligo(ε-caprolactone) allows to access to thermoplastic resins with interesting mechanical properties.

The visual observation of the specimen during the tensile test reported in Fig. 3 may bring some explanations of the phenomenon. Among the hypotheses able to explain the drop of elongation observed, a necking process during uniaxial tensile tests is clearly disregarded since there is no significant reduction in the section of the specimen located during the deformation. It can be seen that the specimens with high deformations whiten during tensile test. This bleaching is even more noticeable as the film is transparent before the test. It could be ascribed to the formation of cavities. In fact, cavitation is manifested by an increase in the inelastic volume and by a modification of the optical properties of the material (bleaching). The deformation profile, where a decrease in the maximum stress during the plastic deformation is observed, is also in agreement with cavitation phenomenons. The elongation at which the fracture occurs depends on the distribution of these cavities, *i.e* localized or in the whole material, and on the number of these cavities. The volume of deformation increases because of the creation of micro-voids while the shear operates without volume variation (Mikus et al., 2014). A more deep study is however necessary to confirm this hypothesis, and will be the subject of a forthcoming paper.

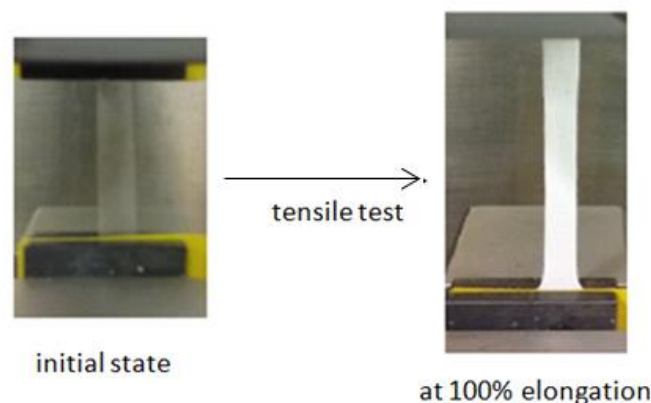


Fig. 3. Evolution of the specimen during mechanical test of the starch-*graft*[poly (butyl acrylate-*co*-styrene acrylate) / oligo (ϵ -caprolactone)] (55% BA / 20% St / 25% CL) obtained by "Radical + ROP" process

4. Conclusions

The dual functionalization of a starch is reported in a one pot one step route in aqueous medium, by combining free radical and ring-opening chemistries. Starch-*graft*-[poly(butyl acrylate)/oligo(ϵ -caprolactone)] and starch-*graft*-[poly(butyl acrylate-*co*-styrene)/oligo(ϵ -caprolactone)] copolymers were synthesized using sodium peroxydisulfate as radical initiator and phosphoric acid as organocatalyst. Compared to the single ring-opening process, an improvement in the grafting percentage of oligo(ϵ -caprolactone) is observed, by a factor of 2 to 4. The DSC analysis showed the presence of two glass transition temperatures, one related to the starch part and the other to the grafted vinyl polymers and being dependent on the butyl acrylate / styrene ratio. Interestingly, the resulting dual functionalized starches shows elongations at break as high as 210 % (BA/St/CL 55/20/25), a 15 fold increase when compared to the single free radical functionalization. The materials show thus promising potentialities in the field of stretchable films for light occulting applications.

CRediT authorship contribution statement

Julie Meimoun: Conceptualization, Investigation, Methodology, Validation, Writing - original draft. Vincent Wiatz: Supervision, Validation. René Saint-Loup: Supervision, Validation, Writing – review. Julien Parcq: Supervision, Validation. Adéline David: Methodology. Grégory Stoclet: Methodology. Valérie Gaucher: Methodology. Audrey Favrelle-Huret: Conceptualization, Supervision, Validation, Writing – review. Fanny Bonnet: Conceptualization, Supervision, Validation, Writing – review. Philippe Zinck: Conceptualization, Methodology, Supervision, Validation, Writing - original draft, Writing – review.

Acknowledgements

The Agence Nationale de la Recherche (ANR) is gratefully acknowledged for the financial support of this project as part of the "Programme d'Investissement d'Avenir". Université de Lille, Chevreul Institute (FR 2638), Ministère de l'Enseignement Supérieur de la Recherche et de l'Innovation, Région Hauts de France are also acknowledged for supporting and funding partially this work. Pr. Eric Deniau is gratefully acknowledged for inspiring discussions on carbohydrate alkoxy radicals.

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